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14. ABSTRACT
ONR grant N00014-98-1-0037, "Arctic Mixed Layer Dynamics," is the last in a series of Arctic Mixed Layer Grants extending over more than 20 years. Throughout that time our approach has been to bring new tools to bear on fundamental questions about mixing in the upper ocean, particularly the mixed layer and under-ice planetary boundary layer. Over the years we have sought to understand the heat and mass balance of the mixed layer, marginal ice zone processes, the Arctic internal wave and mixing environment, summer and winter leads, and convection. In light of recent changes in the upper ocean structure, our long-term goals shifted toward processes important to large-scale changes. Our primary objective under the present grant was to understand the effect of horizontal inhomogeneity on the surface boundary layer during summer.

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Arctic Mixed Layer Dynamics
Final Report

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LONG-TERM GOALS

Our long-term goal has been to understand the dynamic and thermodynamic processes causing changes in the velocity and density structure of the upper Arctic Ocean. For example, over the years we have sought to understand the heat and mass balance of the mixed layer, marginal ice zone processes, the Arctic internal wave and mixing environment, summer and winter leads, and convection. In light of recent changes in the upper ocean structure, our long-term goals shifted toward processes important to large-scale changes.

OBJECTIVES

Our primary objective under the present grant was to understand the effect of horizontal inhomogeneity on the surface boundary layer during summer.

APPROACH

This grant is the last in a series of Arctic Mixed Layer Grants extending over more than 20 years. Throughout that time our approach has been to bring new tools to bear on fundamental questions about mixing in the upper ocean, particularly the mixed layer and under-ice planetary boundary layer. With the sponsorship of the ONR High Latitude Program we have participated in Arctic Ocean experiments bringing to the field a wide range of new technology developed by us and by others. These experiments included NORSEX 79, Fram III (1981), MIZEX 83 and 84, AIWEX (1985), CEAREX 89, LeadEx 91 and 92, SCICEX 93, and SHEBA in 1997-98. With Arctic Mixed Layer grant support the PI served as Chairman-MIZEX Oceanography Sub-group 1982-1984, Chief Scientist CEAREX O Camp 1989, Chairman of the ONR LeadEx Field Operations Group and Chief Scientist of LeadEx Pilot and Main Experiments 1991-92, and a member of the Arctic Science Submarine Cruise Steering (SCICEX) Committee in 1993. New instruments developed under Arctic Mixed Layer and closely related ONR grants include the Arctic Profiling System (APS) for measuring vertical profiles of conductivity, temperature and velocity, the SALARGOS and Polar Ocean Profile temperature-conductivity buoys for long term in situ measurements of temperature and conductivity (which evolved into the Polar Ocean Profile (POP) buoys built for the Naval Oceanographic Office), a computer-controlled yo-yo CTD system, the Autonomous Oceanographic Profiler (AOP) for making unattended vertical profiles of ocean temperature and conductivity (U.S. Patent Number 4,924,698), and the Autonomous Conductivity Temperature Vehicle (ACTV) for making horizontal profiles of ocean temperature and conductivity. The Arctic Mixed Layer Grants have produced 45 publications.

Early work was largely process oriented and included observations of seasonal variations in the upper Arctic Ocean; measurements of oceanographic conditions in the Marginal Ice Zone in the eastern Arctic; discovery of low internal waves energies in the Arctic Ocean and the dependence of this on dissipation of internal wave energy in the under-ice boundary layer, boundary layer, upper ocean and ice observations in the Greenland Sea marginal ice zone; and modeling the partition of

air-ice-ocean momentum exchange as a function of ice concentration, floe size, and draft. Work on the oceanography of leads has gone hand in hand with development of Autonomous Underwater Vehicles and new analysis techniques.

In recent years, dramatic changes in the Arctic Ocean have prompted us to look at large scale phenomena. Work on the first submarine cruise for civilian science in 1993 (SCICEX 93) lead to discovery of major large-scale changes in the Arctic Ocean including a shift in the boundary of Atlantic-derived and Pacific-derived water types. Other work showed the freshening of the upper ocean in the western Arctic. These discoveries lead to the PI's efforts to develop the interagency Study of Environmental Arctic Change project. This has branched out to include the terrestrial and atmospheric environments as well as the marine environment.

The present grant funded the PI to supervise a graduate student, Mr. Dan Hayes, in analyzing data gathered with an Autonomous Underwater Vehicle (AUV) during the Surface Heat Budget of the Arctic Ocean (SHEBA) study. This grew out of our previous efforts using the ACTV to study lead convection, developing a technique to measure vertical water velocity and the turbulent fluxes of heat and salt with Autonomous Underwater Vehicles (AUV), and constructing a vehicle to fully test and exploit the technique. Describing the LeadEx results, Morison and McPhee (1998) used the vertical motion of the ACTV as a proxy for the vertical motion of the water through which it moved. A more accurate technique was sought that would use all available vehicle guidance data and account for the dynamics of the vehicle in the estimation of vertical water velocity. The new technique employs Kalman smoothing. A Kalman filter makes an estimate of the state of a dynamic system that is an optimal combination of the modeled response of the system and instantaneous measurements of the system state. The estimates are optimum in a weighted least square sense, with the weighting dependent on the estimated measurement error and forcing variance. As such, a filter only runs forward in time and can indeed be used in real time. The analysis of vehicle data can be done after all data are collected. In such a case the highest accuracy is obtained by running a Kalman filter forward and backward in time over the data in a process called Kalman smoothing. The first issue in developing the smoothing technique is deriving a system model. The second issue is estimating the measurement errors and the forcing variance. The derived model and error estimates are then used in the Kalman smoothing technique to estimate vertical water velocity. These can be combined with vehicle measurements of temperature and salinity to determine heat and salt fluxes.

RESULTS

The new technique was first developed using existing ACTV data and was then applied to data from a new AUV, the AMTV used at SHEBA. The AMTV was designed to take full advantage of the Kalman smoothing technique. It is based on the Woods Hole Oceanographic Institution's REMotely operated Underwater measurement System (REMUS). Micro-conductivity and micro-temperature sensors are added for heat and salt flux determination. Test runs in local waters were used to verify the new vehicle model used in the smoothing procedure. Runs under Arctic ice at SHEBA were combined with simultaneous measurements of turbulence made with fixed sensors to test the Kalman results and provide a unique view of turbulence in a nonhomogeneous boundary layer. These efforts are described in our paper Hayes and Morison (2002). Additionally Hayes found that good quality spectra could be calculated for the vertical velocities derived by the Kalman smoothing method and that these could be combined with the energy estimates to produce horizontal profiles of vertical momentum flux (stress) using method adapted from McPhee(2003).

The observational results during SHEBA indicate that the scalar quantities, their fluxes, and stress varied substantially in the horizontal. The AMTV run-averaged turbulent stress agrees well with the free-drift estimates. The early summer was characterized by fresh melt water trapped in leads above the draft of the sea ice; this pattern of strong stratification resulting in very weak fluxes. In the middle of summer a storm flushed the fresh melt water from the leads, both horizontally by expanding the lead coverage and vertically by turbulent diffusion and mechanical flushing. Horizontal profiles suggested a pattern of internal turbulent boundary layers growing vertically with

downstream distance from each change in surface flux. An unexpected finding was that even in what is on average a very stable boundary layer environment, there were indications in the character of the boundary layer turbulence that there were regions of decreased stability immediately downstream of lead edges. We think this occurs by virtue of boundary layer shear. When the ice moves over a region that has been warmed and freshened, it drags dense water over less dense water. This reduces the stability locally and promotes mixing even though the average buoyancy flux is stabilizing. A similar effect would apply anywhere there is surface stress and horizontal patchiness in water properties.

To understand the summer lead phenomena observed with the AMTV at SHEBA, Hayes simulated steady, two-dimensional (x and z), forced convection using a simple advective transformation ($x=V_{ice}\,t$). This converts the problem to a one-dimensional (z) time-dependent problem. The method accounts for spatial variability due to growing boundary layers. In this the model was able to simulate some of the key boundary layer behavior observed during SHEBA with the AMTV. However, because it is not truly two-dimensional, the model does not take into account the effects of horizontal pressure variation or allow for the propagation of horizontally inhomogeneous initial conditions. Therefore, the model was not capable of simulating the flushing of a preexisting freshwater lens from a lead or the potential for instability due to the action of vertical velocity shear on such preexisting lenses. Though the model produces growing internal boundary layers subjectively similar to observations, mixing does penetrate as deeply or as quickly as the observations suggest.

To overcome these problems Hayes modified a 3-D model based on one originally developed by David Smith of Arizona State University, and used it in time-varying, 2-D simulations. The model was fine tuned to accurately simulate two periods during SHEBA. One was the flushing event which saw a pre-existing lens of warm, fresh water in the lead mix away over a period of a few days. The other represented the post-flushing period of measurement, a quasi-steady environment in which fresh water continuously entered the ocean through leads and was rapidly mixed in the turbulent boundary layer. The ice velocity was higher in this second period.

Certain improvements to the model were necessary before these periods could be simulated. The improvements included an ice topography boundary condition. This is an arbtrarily shaped top boundary where velocity and salt flux are zero, while temperature is constant. It allows us to simulate for the first time the confinement of a freshwater pool by the walls of the lead. Hayes has also included a predictive equation for temperature, a radiative flux over the lead that decays exponentially with depth, and changed the salinity equation and equation of state to use salinity deviations (improves truncation error). Finally, McPhee's First Order Closure technique for calculating eddy viscosity (McPhee, 1994) has been implemented. In this closure scheme, eddy viscosity is allowed to change in depth and time.

The 3-D runs have been completed for both periods at SHEBA. The agreement with observations is good. Results for both the initial flushing case and the steady flux case are reasonable, with freshwater flushing under the downstream edge of the lead and setting up vertical temperature gradients downstream of the lead in qualitative agreement with our measurements. For example, with this model we find that downstream from the lead edge, temperature profiles are such that heat diffuses both upward and downward away from regions of temperature maximum a few meters below the ice. The results also show that unstable regions occur at the downstream edges of leads soon after the fresh water flux at the lead surface begins. The realistic ice topography implemented in the 3-D model is crticical here. Not only does the topography allow the model to begin with a quiescent pool of fresh water in the lead contained by the surrounding ice, it appears that downstream ice topography is necessary for the instabilities to occur. Shear in the water column in the lee of large topographic features carries salty water from downstream over fresh water flushing out of the lead. Where this occurs, patches of unstable stratification appear. The timing and strength of the meltwater flux and the horizontal variability in surface fluxes have implications for large scales through the the seasonal cyle of mixed layer depth and surface heat budget. These results are described in Hayes' dissertation (Hayes, 2003).

IMPACT/APPLICATIONS

Impacts of this research include providing a technique whereby nearly any AUV can provide turbulence data as a side benefit to other sampling it carries out. Used with simple vehicles, the technique will yield spatial maps of turbulent energy. Used with sophisticated AUVs, the technique will also yield spatial maps of vertical fluxes of the other variables being measured. Such maps will be the keys to identifying dynamically critical areas and determining the budgets of heat, salt, biomass and pollutants. Modeling the effects of horizontal inhomogeneity in surface fluxes provides fundamental knowledge needed to model the dispersion of moisture, heat, and chemical agents from point sources in the atmosphere as well as the ocean.

TRANSITIONS

Vehicles like the AMTV and the Kalman smoothing technique could be used militarily. Such AUVs could make clandestine surveys of littoral areas. The method of extracting information on water motion from vehicle motion would have application in determining the wave energy in areas of military operations. The technique may also find application as a non-acoustic detection and tracking tool. This would find application in "smart" and acoustically quiet weapons that could detect the wakes of vessels and follow them. Torpedoes using the technique in real time could conceivably follow turbulent ship wakes to their targets. Improved understanding of the effects of horizontal inhomogeneity in the planetary boundary layer can be incorporated in homeland security threat assessments of wind-born or water current-borne chemical or biological agents.

RELATED PROJECTS

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